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# Long-term exposure to traffic pollution and hospital admissions in London



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## ABSTRACT

Evidence on the effects of long-term exposure to traffic pollution on health is inconsistent. In Greater London we examined associations between traffic pollution and emergency hospital admissions for cardio-respiratory diseases by applying linear and piecewise linear Poisson regression models in a small-area analysis. For both models the results for children and adults were close to unity. In the elderly, linear models found negative associations whereas piecewise models found non-linear associations characterized by positive risks in the lowest and negative risks in the highest exposure category. An increased risk was observed among those living in areas with the highest socioeconomic deprivation. Estimates were not affected by adjustment for traffic noise. The lack of convincing positive linear associations between primary traffic pollution and hospital admissions agrees with a number of other reports, but may reflect residual confounding. The relatively greater vulnerability of the most deprived populations has important implications for public health.

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## 1. Introduction

A large body of evidence from daily time-series studies has found short-term associations between a range of ambient air pollutants, including those of primary traffic origin, and emergency hospital admissions for cardiovascular and respiratory conditions (WHO, 2013). Evidence for associations with long-term exposure to traffic pollutants, in contrast, is rather mixed (HEI, 2010; WHO, 2013). A systematic review on studies published between 1950 and 2007 found none reporting positive associations between chronic exposure to nitrogen dioxide (NO<sub>2</sub>) or nitrogen oxides (NO<sub>x</sub>) and cardiovascular or respiratory morbidity and concluded that, due to the small number of studies, evidence on these pollutants was insufficient to make solid conclusions (Chen et al., 2008). In 2010, a report on traffic-related air pollution and health

also concluded that the epidemiologic evidence relating to the associations between long-term exposure to primary traffic exposures, for example nitrogen oxides, and health was largely inconclusive (HEI, 2010).

To address this question studies of traffic-related pollution within cities are needed. Population-wide small-area studies which use routinely collected register data have the relative advantage over most cohort studies of individuals of having a larger sample size and greater representativeness, although they are likely to be more vulnerable to residual confounding from unmeasured area and individual-level factors. Previous ecological studies of environmental exposures in London, however, have successfully used small-area methods (Halonen et al., 2015a, 2015b; Hansell et al., 2013).

Therefore, as part of a research programme into the health effects of traffic pollution in London (TRAFFIC study (King's College London, 2014)), we conducted a within-city small-area study of the associations between long-term exposure to primary traffic pollution and hospital admissions for cardiovascular and respiratory diseases for the whole of London between 2003 and 2010. We hypothesized that long-term average pollution contributes to

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exacerbations of existing health conditions resulting in additional hospital admissions observable at the small-area. We used a dispersion model to estimate at a fine spatial scale long-term exposure to six primary traffic pollutants including metrics for exhaust and non-exhaust related primary particles that have rarely been used in previous studies. In addition to the commonly used linear models we used piecewise linear models that relax the assumption of linearity across the whole exposure range.

## 2. Methods

### 2.1. Study area

Our study area comprised all postcode areas within the M25 motorway with over nine million inhabitants. Each postcode is nested within a Census Output Area (COA) that was the spatial unit of analysis ( $n = 27,731$ ). Mean population of COAs is 300 (>40 households) (Office for National Statistics, 2014). We included 27,686 COAs with complete information for the exposures, health outcomes, and possible area-level confounders.

### 2.2. Health outcomes

We selected the first emergency hospital episode in each of the years 2003–2010 recorded in the Hospital Episode Statistics provided by the Health and Social Care Information Centre (HSCIC). We used emergency rather than all (including elective) admissions to better capture exacerbations of disease as opposed to planned visits due to existing diseases. The outcome groups were (ICD-10): all cardiovascular diseases (I00–I99), coronary heart disease (I20–I25), heart failure (I50), stroke (I61, I63, I64), all respiratory diseases (J00–J99), obstructive respiratory diseases (J12–J18 and J20–J22) and infections of the lower respiratory tract (J40–J46). Cardiovascular outcomes were analysed in two age groups: 45–74 and  $\geq 75$  years old, and respiratory outcomes in three age groups: 0–14, 15–64, and  $\geq 65$  years old. We used the sum of admissions across 2003–2010 within each COA. Of all HES admission records in England from 2003 to 2010, 4.2% did not have a valid postcode and were excluded. Annual mid-year population estimates at COA-level by sex and 5-year age band from the Office for National Statistics (ONS) were used to calculate admission rates. The study uses SAHSU data, supplied from ONS; data use was covered by approvals from the National Research Ethics Service - reference 12/LO/0566 and 12/LO/0567 - and by Health Research Authority Confidentiality Advisory Group (HRA-CAG) for Section 251 support (HRA - 14/CAG/1039); superseding National Information Governance Board and Ethics and Confidentiality Committee approval (NIGB - ECC 2-06(a)/2009).

### 2.3. Exposures

We used the KCL urban dispersion model (Beevers et al., 2013; Kelly et al., 2011) to estimate average annual concentrations (2003–2010), as follows: 1) six primary traffic pollutants: nitrogen oxides ( $\text{NO}_x$ ), nitrogen dioxide ( $\text{NO}_2$ ), as well as exhaust (tailpipe emissions) and non-exhaust (brake and tyre wear and re-suspension) related primary  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  (aerodynamic diameter  $< 2.5$  and  $< 10 \mu\text{m}$ , respectively); and 2) five pollutants reflecting the contribution of regional/urban background pollution:  $\text{PM}_{2.5}$ ,  $\text{PM}_{10}$  and ozone ( $\text{O}_3$ ) from which we calculated coarse fraction of  $\text{PM}_{10}$  ( $\text{PM}_{10-2.5}$ ) and oxidative gases ( $\text{O}_x$ , i.e.  $\text{NO}_2 + \text{O}_3$ ) (Williams et al., 2014). The modelling was based on Atmospheric Dispersion Modelling System (ADMS) v.4 and road source model v.2.3, which incorporates hourly meteorological measurements, empirically derived  $\text{NO}-\text{NO}_2-\text{O}_3$  and PM relationships, and

information on source emissions from the London Atmospheric Emissions Inventory (LAEI) (Greater London Authority, 2008). For  $\text{NO}_x$  and  $\text{NO}_2$ , modelled data have been evaluated against measurement data from monitoring sites with an annual data capture of >75%. Minimum number of sites was 62 in 2003, and maximum number was 100 in 2008. The model performed well when validated against measurements: a comparison of observed vs. modelled concentrations provided high spearman correlation coefficients ( $r$ ): for  $\text{NO}_x$   $r$  varied between 0.79 and 0.92, and for  $\text{NO}_2$  between 0.85 and 0.93. More detailed information about the modelling procedure and model validation can be found elsewhere (Beevers and Dajnak, 2015). Spatial resolution of the model was  $20 \times 20 \text{ m}$ ; estimates for each postcode address centroid were based on interpolation between model grid points. COA-level exposure was calculated as the mean of: 1) annual mean concentrations at all postcode address centroids within a COA, and 2) overall study years.

### 2.4. Statistical analyses

Adjacent small areas tend to be more alike than those further apart. To model these spatial dependencies we used ecological Poisson regression specified in a Bayesian framework that was implemented through the Integrated Nested Laplace Approximation (INLA) approach (Rue et al., 2009) using R 3.1.0 package R-INLA ([www.r-inla.org](http://www.r-inla.org)) (Martino and Rue, 2010; R Core Team, 2014). We included age and sex standardised expected numbers of admissions as offsets in the models and accounted for (i) spatial residuals through a conditional autoregressive structure which assumes dependencies between neighbouring areas, and (ii) spatially unstructured variability through an area specific random effect. Minimally informative priors were specified on all the parameters in the model: Gaussian distributions centred on zero and characterised by a precision (1/variance) equal to 0.00001 for the regression coefficients; Gaussian distributions on the two random effects, both centred on zero and characterised by a lognormal (0.5, 0.00005) on the logarithm of the precision.

First we used linear Poisson regression models to determine associations between pollutants and cause-specific hospital admissions. Linear models are most commonly used and thus results can be more reliably compared with prior findings. However, the associations between air pollutants and health outcomes are not necessarily linear. To overcome this issue, categorical variables based on percentiles of the exposure are often used that do not account for changes in the estimates of epidemiological risk (RR/OR) within each category. As a compromise between the two approaches we used piecewise linear models that relax the assumption of linearity of any association across the whole range of exposures. These models use pre-defined exposure categories (here characterised by approximately equal exposure range in each) and assume a (potentially different) linear effect within each category. Models were adjusted for COA-level confounders: quintiles of socioeconomic deprivation; tertiles of proportion of COA population of black and South Asian ethnicities; proxy for smoking (annual smoothed age and sex standardised relative risk of lung cancer mortality (ICD-10: C33–C34)) (Hansell et al., 2013); and daytime road traffic noise ( $L_{Aeq, 16 \text{ h}}$ ). The Carstairs index (Morgan and Baker, 2006) was used as small-area level composite measure of socioeconomic deprivation. Deprivation and ethnicity data were derived from the UK Census 2011, provided by the ONS, and cancer data are derived from national cancer registries and were supplied by the ONS. Annual daytime (from 7:00 to 22:59) road traffic noise levels were modelled at geometric centroids of ~190,000 postcode locations in London using the TRAffic Noise EXposure (TRANEX) (Culliver et al., 2015) model with 0.1 dB(A)

**Table 1**

Distribution of hospital admissions for cardiovascular and respiratory diseases across 27,686 Census Output Areas, London, 2003–2010.

Outcome	Mean	SD <sup>a</sup>	Minimum	P25 <sup>b</sup>	Median	P75 <sup>c</sup>	Maximum	Total n
<b>Cardiovascular</b>								
All 45–74	6.8	4.3	0	4	6	9	69	187,395
All ≥75	6.5	6.3	0	2	5	9	135	179,099
IHD <sup>d</sup> 45–74	2.8	2.4	0	1	2	4	30	77,019
IHD ≥75	1.8	2.1	0	0	1	3	32	48,522
Heart failure 45–74	0.6	1.0	0	0	0	1	10	16,786
Heart failure ≥75	1.3	1.7	0	0	1	2	49	34,951
Stroke 45–74	0.9	1.1	0	0	1	1	12	24,458
Stroke ≥75	1.3	1.8	0	0	1	2	30	35,697
<b>Respiratory</b>								
All 0–14	4.1	3.5	0	2	3	6	48	113,163
All 15–64	5.4	3.9	0	3	5	7	113	149,308
All ≥65	7.2	8.6	0	3	5	9	179	198,899
Infections 0–14	1.7	1.8	0	0	1	2	20	46,217
Infections 15–64	2.0	2.0	0	1	2	3	73	56,595
Infections ≥65	4.2	6.3	0	1	3	5	126	116,292
Obstructive 0–14	0.9	1.3	0	0	0	1	19	25,108
Obstructive 15–64	1.8	2.1	0	0	1	3	22	50,253
Obstructive ≥65	2.4	3.0	0	0	1	3	32	66,979

<sup>a</sup> Standard deviation.<sup>b</sup> 25th percentile.<sup>c</sup> 75th percentile.<sup>d</sup> Ischaemic heart disease.**Table 2**

Distribution of average air pollution concentrations and potential confounding variables across 27,686 Census Output Areas, London, 2003–2010.

Variable	Mean	SD <sup>a</sup>	Minimum	P25 <sup>b</sup>	Median	P75 <sup>c</sup>	Maximum	IQR <sup>d</sup>
<b>Primary traffic pollutant (µg/m<sup>3</sup>)</b>								
NO <sub>x</sub>	66.2	16.2	34.8	54.4	64.0	75.7	178.9	21.3
NO <sub>2</sub>	39.0	6.50	25.4	34.3	38.4	43.0	73.4	8.7
Exhaust related primary PM <sub>2.5</sub>	0.72	0.28	0.28	0.52	0.66	0.85	3.33	0.33
Non-exhaust related primary PM <sub>2.5</sub>	0.73	0.24	0.27	0.55	0.70	0.86	3.17	0.31
Exhaust related primary PM <sub>10</sub>	0.80	0.32	0.30	0.58	0.74	0.95	3.74	0.37
Non-exhaust related primary PM <sub>10</sub>	2.46	0.80	0.98	1.88	2.37	2.91	10.5	1.03
<b>Regional/urban background pollutant (µg/m<sup>3</sup>)</b>								
PM <sub>2.5</sub>	15.3	0.86	13.7	14.7	15.2	15.8	20.0	1.1
PM <sub>10</sub>	24.0	1.50	21.3	22.9	23.8	24.9	36.5	2.0
PM <sub>10-2.5</sub>	8.7	0.71	0.00	8.25	8.66	9.11	19.8	0.86
O <sub>3</sub>	38.7	3.80	24.6	36.0	38.8	41.4	48.3	5.4
O <sub>x</sub> (NO <sub>2</sub> +O <sub>3</sub> )	77.7	2.78	73.4	75.7	77.1	79.1	98.7	3.4
<b>Area-level covariates</b>								
Noise, L <sub>Aeq,16hr</sub> (dB)	58.5	3.58	54.8	55.4	57.4	60.6	78.2	5.2
Deprivation score	0.00	3.18	–5.99	–2.62	–0.45	2.22	13.7	4.5
Black ethnicity (%)	12.0	12.2	0.00	2.86	7.69	17.6	73.2	14.7
South Asian ethnicity (%)	10.2	13.2	0.00	2.41	5.26	11.7	90.8	9.3
Smoking <sup>e</sup>	1.00	0.28	0.29	0.79	0.96	1.16	3.15	0.40

<sup>a</sup> Standard deviation.<sup>b</sup> 25th percentile.<sup>c</sup> 75th percentile.<sup>d</sup> Interquartile range.<sup>e</sup> Smoothed age and sex standardised relative risk for lung cancer mortality.

noise level resolution. For the analyses mean noise levels were aggregated to COA-level.

We tested interactions between continuous exposure and quintiles of socioeconomic deprivation, and ran sensitivity analyses: 1) adjusting models for an “inner-outer London” dummy (13 inner and 20 outer London boroughs) (London Councils, 2014); 2) using different prior distributions in the models; and 3) using 95th percentiles (instead of means) of the air pollution concentrations within the COAs. Because the correlations between pollutants were high (Supplemental Table 1) we confined these sensitivity analyses to associations between NO<sub>x</sub> and all cardiovascular and all respiratory admissions. All results are presented as relative risks (RR) with 95% credible intervals (CI) per “half a range increase” that is based on each pollutant’s exposure categories used for the piecewise models, for example, per 7.5 µg/m<sup>3</sup> for NO<sub>x</sub>.

### 3. Results

#### 3.1. Descriptive statistics

Total numbers and distributions of all outcomes by age groups across COAs are shown in Table 1. Table 2 presents the distributions of average air pollutant concentrations across the COAs. Area-level variation was larger for the primary traffic pollutants (coefficient of variation range 0.17–0.40) compared to the regional/urban background pollutants (coefficient of variation range 0.04–0.10). In Fig. 1 spatial distribution of modelled NO<sub>x</sub> levels over the study area is shown. Correlations between pollutant concentrations were high; for NO<sub>x</sub> in relation to PM concentrations Spearman *r* ranged from 0.94 to 0.98, and for O<sub>3</sub> the range was from –0.92 to –0.99 (Supplemental Table 1). Correlations between pollutants and

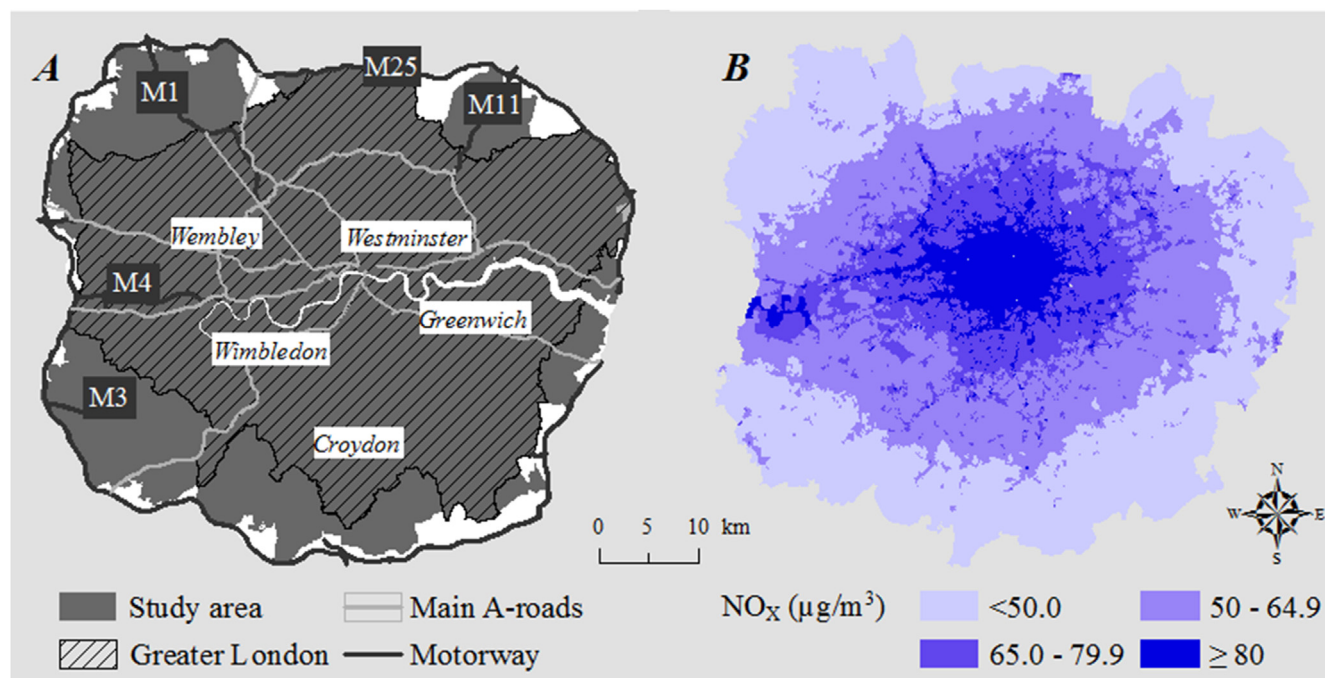


Fig. 1. Map of A) the study area and B) distribution of nitrogen oxide (NOx) concentrations.

Table 3

Adjusted<sup>a</sup> relative risks (RR, 95% credible intervals, CI) for all cardiovascular admissions in association with traffic and regional/urban background pollutants.

Pollutant		All cardiovascular admissions					
		45–74 yr (n = 187,395)			≥75 yr (n = 179,099)		
Primary traffic	Increment µg/m <sup>3</sup>	RR	95% CI		RR	95% CI	
NO <sub>x</sub>	7.5	1.00	0.99	1.01	0.99	0.98	1.00
NO <sub>2</sub>	4.0	1.00	0.99	1.02	0.98	0.97	1.00
Exhaust related primary PM <sub>2.5</sub>	0.15	1.00	0.99	1.01	0.98	0.97	0.99
Non-exhaust related primary PM <sub>2.5</sub>	0.10	1.00	0.99	1.01	1.00	0.99	1.00
Exhaust related primary PM <sub>10</sub>	0.15	1.00	0.99	1.01	0.99	0.98	1.00
Non-exhaust related primary PM <sub>10</sub>	0.50	1.00	0.99	1.01	0.99	0.98	1.00
<b>Regional/urban background</b>							
PM <sub>2.5</sub>	0.60	1.00	0.98	1.02	0.98	0.96	1.00
PM <sub>10</sub>	1.0	1.00	0.99	1.01	0.99	0.97	1.00
PM <sub>10-2.5</sub>	0.35	1.00	0.99	1.01	0.99	0.98	1.00
O <sub>3</sub>	2.5	0.99	0.98	1.01	1.02	1.00	1.04
O <sub>x</sub>	1.5	1.00	0.99	1.01	0.99	0.98	1.00

<sup>a</sup> Models adjusted for age, sex, area-level socioeconomic deprivation, ethnicity, smoking, and daytime road traffic noise.

deprivation index varied by exposure category; correlations between NOx and deprivation by increasing NOx exposure category were: 0.12 (when NOx <50 µg/m<sup>3</sup>), 0.31 (50–64.9 µg/m<sup>3</sup>), 0.10 (65–79.9 µg/m<sup>3</sup>), and –0.06 (≥80 µg/m<sup>3</sup>).

### 3.2. Results from linear models

Linear associations between pollutants and all cardiovascular hospital admissions were close to unity among adults (45–74 years) and the elderly (≥75 years) (Table 3). Effect estimates for all respiratory admissions among children (≤14 years) and adults (15–64 years) were close to one (Table 4). Among the elderly (≥65 years), nearly all effect estimates for all respiratory admissions were slightly below one.

### 3.3. Results from piecewise models for cardiovascular outcomes

Partially and fully adjusted relative risks for all cardiovascular admissions and NOx from the piecewise analyses are presented in

Table 5. Estimates adjusted only for age and sex indicated a clear pattern of higher relative risks at low exposures compared to high exposures. Increasing adjustment for confounders partially attenuated this pattern among adults (45–74 years), but less so among the elderly (≥75 years). Adjustment for smoking, ethnicity, and road noise accounted for the majority of the attenuation in the effect estimates at the lowest exposure range whereas effect estimates at the highest exposure range remained unchanged. Additional adjustment for area-level deprivation had a minor effect. Results from the fully adjusted piecewise analyses for the other primary traffic and all regional/background pollutants are in Supplemental Table 2. Similar to the results for NOx, there was no evidence of an association between any of the pollutants and cardiovascular admissions among adults. Among the elderly, results were similar to NOx with positive associations, i.e. increased risks, in the lowest exposure categories and negative associations, i.e. “protective effects”, in the highest exposure categories.

In association with NOx, the fully adjusted results from



**Table 4**Adjusted<sup>a</sup> relative risks (RR, 95% credible intervals, CI) for all respiratory admissions in association with traffic and regional/urban background pollutants.

Pollutant	Increment $\mu\text{g}/\text{m}^3$	All respiratory admissions							
		0–14 yr (n = 113,163)			15–64 yr (n = 149,308)			$\geq 65$ yr (n = 198,899)	
		RR	95% CI		RR	95% CI		RR	9% CI
Primary traffic									
NO <sub>x</sub>	7.5	1.01	1.00	1.02	1.00	0.99	1.01	0.99	0.97
NO <sub>2</sub>	4.0	1.01	0.99	1.03	0.99	0.98	1.01	0.98	0.96
Exhaust related primary PM <sub>2.5</sub>	0.15	1.01	0.99	1.02	1.00	0.99	1.01	0.98	0.97
Non-exhaust related primary PM <sub>2.5</sub>	0.10	1.00	0.99	1.01	1.00	0.99	1.01	0.99	0.98
Exhaust related primary PM <sub>10</sub>	0.15	1.00	0.99	1.02	1.00	0.99	1.01	0.98	0.97
Non-exhaust related primary PM <sub>10</sub>	0.50	1.00	0.99	1.02	1.00	0.98	1.01	0.99	0.97
<b>Regional/urban background</b>									
PM <sub>2.5</sub>	0.60	1.01	0.99	1.04	0.99	0.97	1.01	0.98	0.96
PM <sub>10</sub>	1.0	1.01	0.99	1.03	0.99	0.98	1.01	0.98	0.96
PM <sub>10-2.5</sub>	0.35	1.00	0.99	1.01	1.00	0.99	1.01	0.99	0.98
O <sub>3</sub>	2.5	0.99	0.97	1.02	1.01	0.99	1.03	1.02	1.00
O <sub>x</sub>	1.5	1.01	0.99	1.02	1.00	0.99	1.01	0.99	0.97

<sup>a</sup> Models adjusted for age, sex, area-level socioeconomic deprivation, ethnicity, smoking, and daytime road traffic noise.**Table 5**Partially and fully adjusted relative risks for all cardiovascular hospital admissions in association with 7.5  $\mu\text{g}/\text{m}^3$  increase in nitrogen oxide.

NO <sub>x</sub>	n COAs	All cardiovascular admissions							
		Mean n of admissions	45-74 yr (n = 187,395)			Mean n of admissions	≥75 yr (n = 179,099)		
			RR	95% CI			RR	95% CI	
Increment 7.5 µg/m <sup>3</sup>									
Partially adjusted 1 <sup>a</sup>									
<50.0	4991	7	1.07	1.01	1.12	9	1.04	0.99	1.08
50–64.9	13,062	7	1.06	1.04	1.09	7	1.03	1.00	1.05
65–79.9	2316	6	1.03	1.01	1.05	5	1.00	0.98	1.02
≥80.0	8115	6	1.02	1.01	1.03	4	0.98	0.96	1.00
Partially adjusted 2 <sup>b</sup>									
<50.0	4991	7	1.03	0.99	1.09	9	1.03	0.98	1.07
50–64.9	13,062	7	1.03	1.01	1.06	7	1.02	0.99	1.04
65–79.9	2316	6	1.02	1.00	1.04	5	1.00	0.98	1.02
≥80.0	8115	6	1.02	1.01	1.03	4	0.98	0.97	0.99
Fully adjusted <sup>c</sup>									
<50.0	4991	7	1.03	0.98	1.07	9	1.03	0.98	1.07
50–64.9	13,062	7	0.99	0.97	1.01	7	1.00	0.98	1.03
65–79.9	2316	6	0.99	0.97	1.01	5	0.99	0.97	1.01
≥80.0	8115	6	1.01	1.00	1.02	4	0.98	0.96	1.00

<sup>a</sup> Models adjusted for age and sex.<sup>b</sup> Models adjusted for age and sex, ethnicity, smoking and daytime road traffic noise.<sup>c</sup> Models adjusted for age and sex, ethnicity, smoking and daytime road traffic noise and area-level socioeconomic deprivation.

piecewise models for heart failure and stroke were similar to those for all cardiovascular diseases, but associations for ischaemic heart disease were close to unity (Supplemental Table 3).

#### 3.4. Results from piecewise models for respiratory outcomes

Partially and fully adjusted results for NO<sub>x</sub> in association with all respiratory admissions from the piecewise analyses are in Table 6. Confounder adjustment had relatively little impact on the estimates among children. In adults and the elderly, the additional confounder adjustment particularly for smoking, ethnicity, and road noise had clear impact on the effect estimates at the low compared to high exposure range.

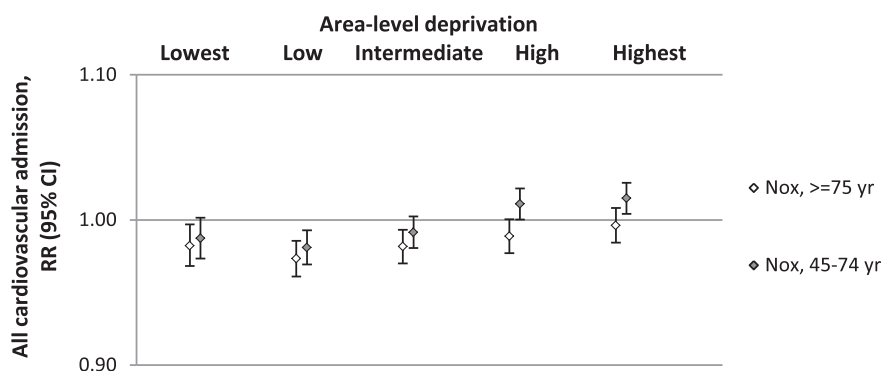
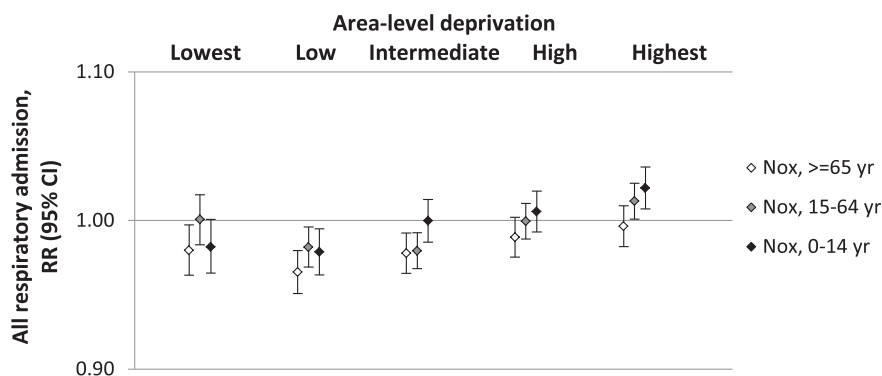
Fully adjusted results for the other primary traffic and all regional/background pollutants with respiratory admissions from piecewise linear models were similar to those for NO<sub>x</sub> (Supplemental Table 4). Associations between NO<sub>x</sub> and obstructive diseases were similar to those for all respiratory diseases in all age groups (Supplemental Table 5). Associations between NO<sub>x</sub> and lower respiratory tract infections among the elderly shared the same non-linear pattern as all respiratory admissions, but we observed no associations in children or adults (Supplemental Table 5).

#### 3.5. Effect modification and sensitivity analyses

Interactions between NO<sub>x</sub> and deprivation in the lowest vs. highest quintile had posterior probabilities (of having an increased risk of hospital admissions with increasing exposure) > 0.95 suggesting effect modification by deprivation. For all cardiovascular admissions the relative risks among adults increased slightly with increasing deprivation; relative risk in the area of lowest deprivation was 0.99 (95% CI 0.97–1.00 per 7.5  $\mu\text{g}/\text{m}^3$  increase in NO<sub>x</sub>) and 1.01 (95% CI 1.00–1.03) in the area of highest deprivation. While differences are small, the finding supports effect modification as the credibility intervals did not overlap. Smaller differences across deprivation quintiles were observed for the elderly (Fig. 2). In associations between NO<sub>x</sub> and all respiratory admissions in children, we also observed this increasing trend by deprivation (Fig. 3). In areas of lowest deprivation relative risk was 0.98 (95% CI 0.96–1.00 per 7.5  $\mu\text{g}/\text{m}^3$  increase in NO<sub>x</sub>) but in areas of highest deprivation the corresponding RR was 1.02 (95% CI 1.01–1.04), which also supports effect modification as the credibility intervals did not overlap. Sensitivity analyses adjusting for the inner-outer London borough, using different priors, or using the 95th percentile of the exposure range had a minor effect on the results (Supplemental Tables 6 and 7).

**Table 6**Partial and fully adjusted relative risks for all respiratory disease hospital admissions in association with 7.5 µg/m<sup>3</sup> increase in nitrogen oxide.

NO <sub>x</sub>	n COAs	All respiratory admissions														
		Mean n of admissions				Mean n of admissions				Mean n of admissions						
		0-14 yr (n = 113,163)				15-64 yr (n = 149,308)				≥65 yr (n = 198,899)						
Increment 7.5 µg/ m <sup>3</sup>			RR	95% CI			RR	95% CI			RR	95% CI				
<b>Partially adjusted 1<sup>a</sup></b>																
<50.0	4193	4		1.04	0.98	1.10	5		1.12	1.05	1.20	8		1.13	1.06	1.20
50–64.9	10,374	4		1.02	0.99	1.05	5		1.06	1.03	1.10	8		1.08	1.05	1.11
65–79.9	8035	4		1.01	0.99	1.03	6		1.04	1.01	1.06	7		1.01	0.99	1.03
≥80.0	5084	4		1.01	1.00	1.02	6		1.00	0.99	1.02	6		0.99	0.97	1.00
<b>Partially adjusted 2<sup>b</sup></b>																
<0.50	4193	4		1.02	0.96	1.08	5		1.06	1.00	1.13	8		1.09	1.03	1.15
0.5–0.79	10,374	4		1.01	0.98	1.05	5		1.04	1.00	1.07	8		1.05	1.02	1.08
0.8–1.09	8035	4		1.01	0.99	1.04	6		1.04	1.01	1.06	7		1.00	0.97	1.03
≥1.1	5084	4		1.02	1.00	1.03	6		1.01	1.00	1.03	6		0.99	0.98	1.01
<b>Fully adjusted<sup>c</sup></b>																
<0.50	4193	4		1.02	0.96	1.08	5		1.04	0.99	1.10	8		1.08	1.02	1.14
0.5–0.79	10,374	4		1.00	0.97	1.03	5		0.98	0.95	1.00	8		1.01	0.98	1.04
0.8–1.09	8035	4		1.00	0.98	1.03	6		1.00	0.98	1.02	7		0.98	0.95	1.00
≥1.1	5084	4		1.01	1.00	1.03	6		1.00	0.99	1.01	6		0.98	0.97	0.99

<sup>a</sup> Models adjusted for age and sex,<sup>b</sup> Models adjusted for age and sex, ethnicity, smoking and daytime road traffic noise<sup>c</sup> Models adjusted for age and sex, ethnicity, smoking and daytime road traffic noise and area-level socioeconomic deprivation**Fig. 2.** Adjusted<sup>a</sup> associations between an interquartile range increase in nitrogen oxides (NO<sub>x</sub>) concentration and all cardiovascular hospital admissions among adults and the elderly by quintiles of area-level deprivation. <sup>a</sup>Models adjusted for age, sex, ethnicity, smoking and daytime road traffic noise.**Fig. 3.** Adjusted<sup>a</sup> associations between an interquartile range increase in nitrogen oxides (NO<sub>x</sub>) concentration and all respiratory hospital admissions among children, adults and the elderly by quintiles of area-level deprivation. <sup>a</sup>Models adjusted for age, sex, ethnicity, smoking and daytime road traffic noise.

#### 4. Discussion

Our comprehensive and statistically powerful analysis of air pollution and hospital admissions for cardiovascular and respiratory diseases in the whole population of London found little evidence of positive associations. Some non-linear associations

were observed, especially in the elderly, which took the form of inverse J-shaped dose response. For some outcomes there was evidence of effect modification by area-level socioeconomic deprivation, with an increasing trend across deprivation quintiles and small but significant positive associations in the highest deprivation group.

#### 4.1. Methodological issues

Our hypothesis was that increased long-term exposure to air pollutants, especially those from traffic sources, increases the risk of exacerbation of cardiovascular and respiratory diseases and that this is reflected in emergency hospital admissions for these conditions. It is already known from many time-series studies, including some from London, that short-term exposure to a range of gaseous and particulate pollutants measured at city monitors is associated with increased hospital admissions (Atkinson et al., 1999; WHO, 2013). The postulated mechanism is acute exacerbation of disease in an individual already on the brink of admission. It is not known to what extent such increases in risk represent the bringing forward in time of an inevitable admission, or cause an additional admission that would not have otherwise occurred. It is only in the latter scenario that there would be an increase in admission rates detectable in a small-area analysis with disease counts aggregated over many years.

Whereas time-series analyses control by design spatial confounding factors that are relatively stable over time, small-area analyses such as ours are vulnerable to spatial confounding. This is especially the case for hospital admissions which reflect not only aetiological factors responsible for the development of disease and the incidence of exacerbating factors, but complex organisational and behavioural factors (Anderson, 1978) which do not relate to the severity of disease and which cannot be accounted for by crude measures of deprivation. At the outset we were aware of the potential for spatial confounding and had planned a change on change analysis at postcode level which would be more robust to spatial confounding. However, temporal changes over the period 2003–2010 were very similar spatially and too small for this approach to be adopted and we therefore chose to use a small-area approach which had been applied successfully in previous studies (Halonen et al., 2015a, 2015b; Hansell et al., 2013). Our analytic approach using conditional autoregressive models will have captured some unmeasured spatial confounders, and in addition to age and sex, we controlled for area-level smoking, ethnicity, road traffic noise and socioeconomic deprivation. Nevertheless, we cannot exclude the possibility of residual confounding. For example, the piecewise model found lower risks in areas of highest exposures and some of the highest exposures are in extremely wealthy areas of central London. Thus, use of the Carstairs index, may not have been sufficient to adequately adjust for socioeconomic status because one of its components (car ownership) is likely to represent different social status in the inner (more affluent) parts of the city than elsewhere.

The fine scale dispersion model employed to estimate long-term exposures has been used extensively for traffic planning in London (Greater London Authority, 2010) and performed well when validated against measurements. However, due to lack of covariate data and low numbers of admissions at postcode level, the aggregation of postcodes to COAs was associated with a loss of variability in exposure estimates for the pollutants. Nevertheless, the variability of primary traffic pollutants remained clearly greater than that of urban background pollutants such as PM<sub>2.5</sub>.

#### 4.2. Comparison with literature

Overall, we found little evidence for positive linear associations between air pollution and hospital admissions in London. Our estimates were characterised by narrow confidence intervals; thus the lack of associations could not be explained by a lack of statistical power. Our results are generally in line with the available literature which comprises few if any studies of equivalent power. Several recent studies, many of which are based on cohort data, have

examined the effects long-term exposure to markers of traffic exposure: NO<sub>2</sub> and NO<sub>x</sub>. A summary of these studies (Table 7) shows that nearly half of the studies reported positive and statistically significant associations, a few others reported positive non-significant associations, and the rest reported no associations. Positive associations were more common for respiratory than cardiovascular outcomes, and the respiratory effects were often observed either among older population groups or in children. We also observed the strongest positive associations for respiratory outcomes among the elderly although only at the lowest exposures.

As the associations between air pollutants and health outcomes are not necessarily linear we used piecewise linear models that can identify non-linear relationships and are more easily interpreted than more flexible and complex models like cubic splines. That the strongest positive associations were observed in the lowest exposure category particularly for some outcomes among the elderly is likely due to differential residual confounding, as adjustment for area-level confounders had a greater impact on the effect estimates in the low than high exposure category. However, it should be noted that concentration response functions relating air pollution to health outcomes are not infrequently observed to be steeper at low concentrations and flatten out at higher concentrations. This is illustrated by the integrated exposure response curves derived from combining cohort results for various sources of pollution that are much steeper at low concentrations (Burnett et al., 2014). This pattern has also been reported, for example, for ambient PM<sub>2.5</sub> concentration in association with cardiovascular mortality (Pope et al., 2011), and for NO<sub>2</sub> and PM<sub>2.5</sub> with IHD mortality (Cesaroni et al., 2013; Crouse et al., 2012). However, none of these studies observed a decline in association at higher exposure as we did. Due to different study methods, previous findings are not directly comparable to ours and further research using similar piecewise regression methods are needed to make solid conclusions.

Few studies have examined the modifying role of area-level deprivation on the associations between traffic pollution and health. No effect modification by area deprivation was observed by Atkinson et al., 2015 in their study that examining first COPD admissions in an English cohort (Atkinson et al., 2015). However, in their earlier work, associations between NO<sub>2</sub> and heart failure incidence were stronger in the least versus most deprived areas (Atkinson et al., 2013). In our study, area-level socioeconomic deprivation seemed to slightly modify the associations for traffic pollutants with all cardiovascular admissions among adults, and with all respiratory admissions among children, with small but significant positive associations in the highest deprivation group observed.

#### 4.3. Strengths and limitations

Our study of all London residents' benefits from the large number of events included, its representativeness, and consistency of characterisation of outcomes, exposure, and confounding factors. This is in contrast to cohort studies, which are often underpowered for the investigation of major events, subject to attrition, and unrepresentative of the population. Conversely, cohort studies are not prone to the ecological fallacy whereby observed risks for small areas may not apply to all individuals in that area. Both cohort studies and the present study design are prone to problems of exposure characterisation (e.g. lack of time-activity patterns), but have to a variable extent the advantage of using individual-level confounding data such as smoking habit, residential history and exposure earlier in life. Many cohort studies to date have lacked data on neighbourhood-level socioeconomic indicators (de Kluizenaar et al., 2013; Katsoulis et al., 2014; Miller et al., 2007; Molter et al., 2014; Neupane et al., 2010) which can be a source of



**Table 7**

Summary table on the literature on associations between traffic related air pollution and morbidity from year 2005.

Author, year	Study design	Location	Population, n (age year)	Traffic exposure	Outcome	Finding <sup>a</sup>
<b>Cardiovascular</b>						
Maheswaran et al., 2005b	Ecological	England	308,841 ( $\geq 45$ )	NO <sub>x</sub>	CHD <sup>b</sup> admission	–
Maheswaran et al., 2005a	Ecological	England	199,682 ( $\geq 45$ )	NO <sub>x</sub>	Stroke admission	+
Johnson et al., 2010	Ecological	Canada	1,034,945	NO <sub>2</sub>	Stroke admission	–
Miller et al., 2007	Cohort	USA, 36 MSA <sup>d</sup>	65,893 women (50–70 at baseline)	NO <sub>2</sub>	All CVD <sup>c</sup> events	–
Cesaroni et al., 2014	Cohort	11 ESCAPE	100,166 (44–74 at baseline)	NO <sub>2</sub> , NO <sub>x</sub> , PM <sub>2.5</sub> abs <sup>e</sup>	Acute coronary events	–
Rosenlund et al., 2008	Cohort	Italy	Residents of Rome (35–84)	NO <sub>2</sub>	First coronary event	+
Katsoulis et al., 2014	Cohort	Greece	1504 women	NO <sub>2</sub>	CHD <sup>b</sup> incidence	+
Atkinson et al., 2013	Cohort	England	836,557 (40–89 at baseline)	NO <sub>2</sub>	Heart failure	+
Atkinson et al., 2013	Cohort	England	836,557 (40–89 at baseline)	NO <sub>2</sub>	MI, arrhythmia, stroke incidence	–
Lipsett et al., 2011	Cohort	CA, USA	12,172–15,149 (postmenopausal women)	NO <sub>x</sub> , NO <sub>2</sub>	MI, stroke, incidence	–
de Kluizenaar et al., 2013	Cohort	Netherlands	18,213 ( $\geq 65$ )	NO <sub>2</sub> , EC	CHD <sup>b</sup> , cerebrovascular admission	–
Katsoulis et al., 2014	Cohort	Greece	2752 (47 at baseline)	NO <sub>2</sub>	All CVD <sup>c</sup> , stroke incidence	–
Stafoggia et al., 2014	Cohort	11 ESCAPE	99,446 (44–74 at baseline)	NO <sub>2</sub> , NO <sub>x</sub> , PM <sub>2.5</sub> abs <sup>e</sup>	Cerebrovascular, incident	–
Sorensen et al., 2014	Cohort	Denmark	57,053 (50–64 at baseline)	NO <sub>2</sub>	Stroke, incident	–
Andersen et al., 2012b	Cohort	Denmark	57,053 (56 at follow-up)	NO <sub>2</sub>	Stroke, incident	weak
Rosenlund et al., 2006	case–control	Sweden	1379 + 1870 (45–70)	NO <sub>2</sub>	MI, overall	–
<b>Respiratory</b>						
Rushworth et al., 2014	Ecological	England	Residents of Greater London	NO <sub>2</sub> , NO <sub>x</sub>	All respiratory admissions	weak
Andersen et al., 2011	Cohort	Denmark	57,053 (56 at baseline)	NO <sub>2</sub> /NO <sub>x</sub>	COPD <sup>f</sup> admission	+ / weak
Schikowski et al., 2014	Cohort	3 ESCAPE	6550 (34–54 at baseline)	NO <sub>2</sub> , NO <sub>x</sub> , PM <sub>2.5</sub> abs <sup>e</sup>	COPD <sup>f</sup> incidence	–
Atkinson et al., 2015	Cohort	England	812,063 (40–89 at baseline)	NO <sub>2</sub>	COPD <sup>f</sup> admission	weak
MacIntyre et al., 2014	Cohort	10 ESCAPE	16,059 (up to 3)	NO <sub>2</sub> , NO <sub>x</sub>	Diagnosed pneumonia	+
Andersen et al., 2012a	Cohort	Denmark	50–65 at baseline	NO <sub>2</sub>	Asthma admission	+
Young et al., 2014	Cohort	USA	39,350 (55, women)	NO <sub>2</sub>	Asthma, incident	–
Modig et al., 2009	Cohort	Sweden	3609 (39 at baseline)	NO <sub>2</sub>	Asthma, onset/incident self-reported	+
Yamazaki et al., 2014	Cohort	Japan	10,069 (6–9 at baseline)	EC <sup>g</sup> /NO <sub>x</sub>	Asthma, incident	+ / weak
Oftedal et al., 2009	Cohort	Norway	2871 (9–10)	NO <sub>2</sub> (lifetime)	Asthma, onset	–
Jerrett et al., 2008	Cohort	CA, USA	217 (10–18 at baseline)	NO <sub>2</sub>	Asthma, onset	+
McConnell et al., 2010	cohort	CA, USA	2497 (5–9 at baseline)	NO <sub>2</sub>	Asthma, incidence	+
Molter et al., 2014	(birth) cohort	England	1158 (3–11)	NO <sub>2</sub>	Asthma prevalence	–
Gruzdeva, 2013	(birth) cohort	Sweden	4089 (0–12)	NO <sub>x</sub>	Asthma, incident at 12 yr	+
Neupane et al., 2010	case–control	Canada	345 + 494 ( $\geq 65$ )	NO <sub>2</sub>	Pneumonia	+
Modig et al., 2006	case–control	Sweden	203 + 203 (20–60)	NO <sub>2</sub>	Asthma, incident	weak
Clark et al., 2010	Nested case–control	British Columbia	37,401	NO <sub>2</sub>	Asthma, incidence	+
Anderson et al., 2013	Meta-analysis			NO <sub>2</sub>	Asthma	+

<sup>a</sup> Finding: “–” means no or negative association, “+” means positive statistically significant association, and “weak” means positive statistically non-significant association.<sup>b</sup> Coronary heart disease.<sup>c</sup> All cardiovascular diseases.<sup>d</sup> Metropolitan Statistical Areas.<sup>e</sup> PM<sub>2.5</sub> absorbance.<sup>f</sup> Chronic obstructive pulmonary disease.<sup>g</sup> Elemental carbon.

additional confounding, whereas our study did not have data on individual-level confounders nor residential mobility. Having secondary housing outside London, for example, where air pollution exposure is likely to be lower, may be more common among the more affluent residents of the more polluted inner boroughs (City of London, Westminster, and Kensington and Chelsea (Office for National Statistics, 2012)) than in outer London boroughs. This may have added to the exposure misclassification and masked some positive associations in the high exposure group. It may also, in part, help to explain the observed effect modification by deprivation, with lowest risks in lowest deprivation quintiles. We did not know the spatial distribution of the excluded admission records without valid geographical information, and thus cannot say how many would have been in London (the study area) or whether their spatial distribution was non-random. However, when we mapped the hospital admissions they did not suggest missing data

corresponding to particular areas. Also, as the percentage was rather small, we suspect this factor is unlikely to bias our results. Finally, some significant associations may also have occurred due to chance due to multiple testing of different outcomes and exposures.

#### 4.4. Conclusions

Overall, in this large and statistically powerful study within London we found no convincing positive linear associations, which is in line with much of the existing literature generally based on smaller studies. The piecewise analyses revealed positive associations in the low and negative associations in the high exposure categories potentially due to differential residual confounding, but this finding needs to be replicated in other studies. There was evidence of effect modification with area-level socioeconomic

deprivation, with those living in areas of higher deprivation having the greatest risk of hospital admission. Increased vulnerability of the most deprived groups in urban centres, chronically exposed to air pollution over the long-term, will have important implications for public health.

## Conflicts of interest

The authors declare no conflicts of interest.

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## Contributions

JIH contributed to the study design, statistical script, and data analyses, and drafted the report. MB contributed to the study design and statistical script. DF, JG, SDB, DD, HRA and FJK contributed to exposure assessment. MBT, JG, HRA, SDB, FJK and CT contributed to the funding and study design. All authors contributed to critical reading of, and commented on the report, helped to interpret the data, and approved the final draft.

## Submission declaration

The authors that the work described has not been published previously, that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere including electronically in the same form, in English or in any other language, without the written consent of the copyright-holder.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.envpol.2015.09.051>.

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